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Using the regression estimator with Landsat data to estimate proportion forest cover and net proportion deforestation in Gabon

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Forest cover maps were produced for the Gabonese Agency for Space Studies and Observations (AGEOS) for 1990, 2000 and 2010 for an area of approximately 102,000 km^2 corresponding to 38% of the total area of Gabon and representative of the range of human pressure on forest resources. The maps were constructed using a combination of a semi-automated classification procedure and manual enhancements to ensure the greatest possible accuracy. A two-stage area frame sampling approach was adopted to collect reference data for assessing the accuracy of the forest cover maps and to estimate proportion forest cover and net proportion deforestation. A total of 251 2 × 2 km segments or primary sample units (PSUs) were visually interpreted by a team of photo-interpreters independently from the map production team to produce a reference dataset representing about 1% of the study area. Paired observations were extracted from the forest cover map and the reference data for a random selection of 50 secondary sample units (SSUs) in the form of pixels within each PSU. Overall map accuracies were greater than 95%. PSU and SSU outputs were used to estimate proportion forest cover and net proportion deforestation using both direct expansion and model-assisted regression (MAR) estimators. All proportion forest cover estimates were similar, but the variances of the MAR estimates were smaller than variances for the direct expansion estimates by factors as great as 50. In addition, SSU-level estimates had standard errors slightly greater than those of PSU-level estimates, but the differences were small, particularly when auxiliary variables were obtained from forest cover maps. Therefore, a two-stage sampling approach was justified for collecting a reliable forest cover reference dataset for estimating proportion forest cover area and net proportion deforestation. Finally, despite large overall map accuracies, net proportion deforestation estimates obtained from the maps alone can be misleading as indicated by the finding that the MAR estimates, which included adjustment for bias estimates, were twice the non-adjusted map estimates for the periods 1990–2000 and 1990–2010. The results confirmed the expected generally small level of net deforestation for Gabon. However, loss of forest cover appears to have almost stopped in the last 10 years. One explanation could be the creation of national parks and the implementation of forest concession management plans from 2000 onward, but this should be further explored.

1. Introduction

1.1. Forest cover monitoring in central Africa

The role of tropical forests as the largest reservoir of biodiversity and as a major carbon sink is well-recognized. The Central African forest is the second largest tropical forest area after the Amazon, but it is still relatively well-preserved, making its conservation and management all the more crucial (de Wasseige et al., 2012; Justice, Wilkie, Zhang, Brunner, & Donoghue, 2001). Although uncertainties are large (Achard et al., 2002), tropical deforestation and forest degradation are estimated to contribute approximately 20% of all greenhouse gas (GHG) emissions (Achard et al., 2007; Gullison et al., 2007). Therefore, reducing tropical deforestation and degradation can have a direct impact on the reduction of GHG emissions.

Consequently, the post-Kyoto protocol mechanism, Reduction of Emissions from Deforestation and forest Degradation (REDD), was proposed and initiated at the UNFCCC Conference of Parties (COP) 11 in Montréal in 2005. GHG inventories as part of the UNFCCC process require two inputs: activity data and emissions factors (IPCC, 2006). In the REDD context, activity data refer to the extent of forest cover and forest cover change and require spatially explicit estimates (GOFC-GOLD, 2011). Emissions factors refer to quantities of GHG emissions per unit area for an activity and rely primarily on field inventory data for estimation. Thus, monitoring of forest cover and forest cover change by means of a robust and transparent national forest monitoring system is a pre-requisite for a national REDD policy. The Gabonese Agency for

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Space Studies and Observations (AGEOS) was established in 2010 with the aims of implementing a national infrastructure for environmental monitoring and mitigating the impacts of climate change. In addition, the AGEOS objectives included building the capacity to monitor forest cover at the national level.

Although national forest monitoring systems could rely solely on information acquired by ground sampling, the budgetary and logistical constraints associated with intensive sampling of remote and inaccessible forests make this option infeasible for many tropical countries. For these countries, maps in the form of classifications of multi-spectral satellite imagery are routinely recommended as another source of information for forest cover and forest cover change. However, a crucial difference between ground sample observations and maps based on classified imagery must be noted. Whereas ground sample observations are assumed to be observations without error, apart from minimal measurement error, maps based on satellite image classifications are predictions and include varying degrees of inherent uncertainty. Thus, complete reliance on image-based estimates of forest cover and forest cover change entails considerable risk if no compensation is made for bias resulting from systematic classification errors. In particular, satellite imagery should not be used apart from a sample of reference data for purposes of estimating both bias and uncertainty.

Duveiller, Defourny, Desclée, and Mayaux (2008) and Ernst et al. (2013) used approaches based on a systematic sampling of classified satellite image extracts to estimate regional and country-level net deforestation for Central Africa. However, both studies emphasized that estimates for three of six countries, including Gabon, were less reliable due to the lack of sufficient cloud-free imagery. Obviously, augmentation of ground sampling with wall-to-wall mapping is more expensive than simply ground sampling. Nevertheless, wall-to-wall land cover maps fulfill several functions when monitoring forest cover change: (1) they can be used to augment ground data and thereby enhance estimates based solely on ground sample data; (2) they can serve as a reference baseline against which future change can be assessed; and (3) they can be used to assess the impact of forest management policies and for legal enforcement. For an appropriate interpretation of results, Achard et al. (2007) emphasized the need for a consistent methodology and spatial resolution. Wall-to-wall mapping was also applied to the Congo basin region by Hansen et al. (2008), and although country-level forest cover estimates were based on 250×250-m resolution MODIS data, forest cover change estimates based on the combination of MODIS and Landsat were only reported for three broad landscape areas. These examples highlight the need to adopt a national-level approach to ensure that country specific situations are accommodated.

Gabon is recognized as one of the cloudiest areas of the Congo basin and in Africa more generally. Therefore, a specific approach is required to produce country level estimates of forest cover and forest cover change. Hansen et al. (2008) addressed the issue of persistent cloud cover in the Congo Basin region by combining fine and medium spatial resolution imagery despite the potential loss of spatial detail. Zhu, Woodcock, and Olofsson (2012) suggested using the entire Landsat archive available for a given area to monitor forest disturbance on a continuous basis, although such an application has only become possible since the Landsat archive has been made freely available.

Central Africa is also one of the few blind spots in terms of Earth Observation (EO) data acquisition because no satellite receiving station covers the area. Thus, when the Landsat 4 TM instrument failed in the early 1990s and Landsat 5 lost its transmission via a Geostationary satellite in 1992 (Loveland & Dwyer, 2012), only direct reception remained possible. Unfortunately, no Landsat 5 acquisition was possible over most of Central Africa until the launch of Landsat 7 in 1999. In addition, Landsat data distribution was relinquished to a commercial company in the mid-1980s, causing further disruption in the consolidation of the global Landsat archive (Wulder, Masek, Cohen, Loveland, & Woodcock, 2012). Despite these difficulties, Landsat data still provide the best EO data coverage of the country since the late 1980s, because few other sensors have been available over such a long period. Little SPOT imagery was acquired until recently, and IRS data are rarely acquired for Africa. Due to the complexity of its use and lack of availability for Gabon, SAR data is recommended only for gap filling by the REDD Source Book (GOFC-GOLD, 2011).

Multiple reports of forest cover and cover change area estimates at regional or global levels have been published (Achard et al., 2002; Duveiller et al., 2008; Ernst et al., 2013), but estimates are either not available at the country level or the authors themselves acknowledge that the data are less reliable for some countries. In addition, the IPCC (2006) specifically notes that good practice requires that estimates should be accompanied by measures of uncertainty. Error or confusion matrices (Congalton, 1991) and their associated measures of accuracies (Stehman, 1997) are starting points for assessing uncertainty. However, the measures of accuracy estimated from confusion matrices do not directly provide uncertainty measures in the form of confidence intervals as are required to assess the significance of the changes in estimates of forest cover (McRoberts, 2011). An approach based on a statistical, model-assisted, regression estimator that satisfies this requirement was developed in the 1970s and 1980s for crop statistics (Allen, 1990; Carfagna & Gallego, 2005; Gallego, 2004; Taylor, Sannier, Delincé, & Gallego, 1997) and was successfully applied to estimating forest cover over a small study area in Southern Brazil by Deppe (1998). A similar approach using satellite data was used by McRoberts and Walters (2012) and McRoberts (2014) to estimate net deforestation in the United States of America and by Vibrans, McRoberts, Moser, and Nicoletti (2013) to estimate forest cover in Brazil.

1.2. Aim and objectives

The aim of this study was to develop and illustrate statistically rigorous methods for estimating proportion forest cover and net proportion deforestation that are suitable for use in tropical countries such as Gabon. For purposes of demonstrating applicability at a national scale, a large study area was selected (Section 2), and the relevant reference years of 1990, 2000, and 2010 were selected. A secondary objective was to determine the relative merits of a two-stage sampling design that would potentially require less effort to implement, compared with a one-stage sampling design, for a pre-operational forest cover monitoring system in Gabon with potential for application in other tropical high forest cover countries.

The study makes no attempt to identify the type of forest cover change (GOFC-GOLD, 2011), but focuses on estimating proportion forest cover and net proportion deforestation where net deforestation is the net result of gross deforestation, afforestation, and reforestation and is assumed to be attributed solely to human activity. The technical approach combined sample-based data collection and wall-to-wall mapping using a regression estimator to estimate proportion forest cover, net proportion deforestation, and their uncertainties. One-stage and two-stage estimators were used to assess the contributions of the wall-to-wall, image-based maps with respect to increasing accuracy and precision and with respect to the ease of data collection.

2. Data

2.1. Study area

Gabon is an equatorial country located in the Congo basin region of Central Africa with a total area, including land and water, of 267,667 km^2 (CIA, 2009). A small population and substantial oil and mineral resources contribute to making Gabon one of the wealthiest countries in Africa. One consequence is that equatorial forest cover in Gabon is among the greatest in the world, and most of it has been preserved. Gabon's location on the Equator and on the Atlantic Ocean